

TANDEM SOLAR CELL AND METHOD OF FABRICATING THE SAME

BACKGROUND

5 Technical Field

The present disclosure relates to the field of solar cell. More particularly, the present disclosure relates to a tandem solar cell and a method of fabricating the same.

10 Description of Related Art

As a source of a renewable clean energy, solar cell is getting more and more attention. Historically, the solar cell is normally divided into three phases: "the first generation" is a solar cell taking silicon chip as a substrate, which has been a mature techniques but with the high cost in silicon-chip growth; the
15 "second generation" is a thin-film solar cell with lower production cost developed in the past decade, wherein multiple solar cell modules are allowed in a single solar cell substrate. As the next generation of the promising technology, a tandem solar cell is becoming one of major research tops.

The structure of a traditional tandem solar cell is shown in Fig. 1. The
20 solar cell includes a substrate 1, a transparent conductive oxide (TCO) layer 2 formed on the substrate 1, a top p-i-n structure 3 formed on the transparent conductive oxide layer 2, a bottom p-i-n structure 4 formed on the top p-i-n structure 3, and a back metal layer 5 formed on the bottom p-i-n structure 4. The top p-i-n structure 3 includes a P-type amorphous silicon layer 31, an I-type
25 amorphous silicon layer (i.e., an intrinsic amorphous silicon layer) 32 and an



N-type amorphous silicon layer 33 which are stacked in sequence, wherein the P-type amorphous silicon layer 31 is formed on the transparent conductive oxide layer. The bottom p-i-n structure 4 includes a P-type microcrystalline silicon layer 41, an I-type microcrystalline silicon layer (i.e., an intrinsic microcrystalline silicon layer) 42 and an N-type microcrystalline silicon layer 43 which are stacked in sequence, wherein the P-type microcrystalline silicon layer 41 is formed on the N-type amorphous silicon layer 33. Sunlight is absorbed by the I-type amorphous silicon layer 32 of the top p-i-n structure 3 and the I-type microcrystalline silicon layer 42 of the bottom p-i-n structure 4 to generate an electron-hole pair. An electric field generated between the P-type layer (the P-type amorphous silicon layer or the P-type microcrystalline silicon layer) and the N-type layer (the N-type amorphous silicon layer or the N-type microcrystalline silicon layer) enables an electron to move towards the N-type layer and enables a hole to flow towards the P-type layer, so as to form a current, and thus light energy is converted into electric energy. Since the band gap of the amorphous silicon is larger than the band gap of the microcrystalline silicon, the microcrystalline silicon is able to absorb light in a wave band wider than that absorbable by the amorphous silicon. In a solar cell with this structure, sunlight first irradiates the top p-i-n structure 3 and is absorbed by the I-type amorphous silicon layer 32, and sunlight which is not absorbed by the top p-i-n structure 3 reach the bottom p-i-n structure 4 and is absorbed by the I-type microcrystalline silicon layer 42.

The photoelectric conversion efficiency is an essential factor of evaluating a solar cell. Nowadays, with the shortage in energy resources, exploring a solar cell with high photoelectric conversion efficiency becomes

more and more important. The photoelectric conversion efficiency of the solar cell in the art achieve more or less improvement but still insufficient. Therefore, there is still a need to provide a solar cell with higher photoelectric conversion efficiency.

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SUMMARY

The present disclosure provides a tandem solar cell with high photoelectric conversion efficiency and a production method thereof.

10 In order to realize the above aspect, the tandem solar cell provided by the present disclosure includes: a substrate; a transparent conductive oxide layer formed on the substrate; a top p-i-n structure formed on the transparent conductive oxide layer and including a first p-i-n structure, wherein the first p-i-n structure includes a P-type amorphous silicon layer, an I-type amorphous silicon
15 layer and an N-type amorphous silicon layer which are stacked in sequence, and the P-type amorphous silicon layer is adjacent to the transparent conductive oxide layer; a bottom p-i-n structure formed on the top p-i-n structure, wherein the bottom p-i-n structure includes a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline
20 silicon layer which are stacked in sequence, and the P-type microcrystalline silicon layer is adjacent to the top p-i-n structure; a stress inducing layer formed on the bottom p-i-n structure, wherein the stress inducing layer induces tensile stress in the bottom p-i-n structure; and a back metal layer disposed on the stress inducing layer.

As an embodiment, the stress inducing layer is made of tungsten, silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride.

As an embodiment, the stress inducing layer has a thickness of 10 nm-500 nm.

5 As an embodiment, a buffer layer is formed between the top p-i-n structure and the bottom p-i-n structure.

As an embodiment, the buffer layer is made of porous silicon containing P-type dopant or N-type dopant.

10 As an embodiment, the aperture diameter of the porous silicon is smaller than 1 μm .

As an embodiment, the top p-i-n structure further includes a second p-i-n structure with an I-type layer disposed on the first p-i-n structure, wherein the band gap of the I-type amorphous silicon layer of the first p-i-n structure is larger than the band gap of the I-type layer of the second p-i-n structure.

15 As an embodiment, the second p-i-n structure includes a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer which are stacked in sequence or a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type amorphous silicon layer which are stacked in sequence.

20 As an embodiment, the energy band gap of the I-type microcrystalline silicon layer of the second p-i-n structure is gradually reduced along the direction from the substrate to the back metal layer.

In order to realize the above aspect, the present disclosure also provides a method of fabricating a tandem solar cell, including the steps of: providing a
25 substrate; forming a transparent conductive oxide layer on the substrate;

forming a top p-i-n structure on the transparent conductive oxide layer, which comprises a first p-i-n structure, wherein the first p-i-n structure comprises a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type amorphous silicon layer which are stacked in sequence, wherein the
5 P-type amorphous silicon layer is close to the transparent conductive oxide layer; forming a bottom p-i-n structure on the top p-i-n structure, the bottom p-i-n structure comprising a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer which are stacked in sequence, wherein the P-type microcrystalline silicon layer is
10 adjacent to the top p-i-n structure; forming a stress inducing layer on the bottom p-i-n structure, wherein stress inducing layer induced tensile stress in the bottom p-i-n structure during forming process of the stress inducing layer; and forming a back metal layer on the stress inducing layer.

As an embodiment, the stress inducing layer is formed by utilizing a
15 chemical vapor deposition process.

As an embodiment, the stress inducing layer is made of tungsten, silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride.

As an embodiment, the thickness of the stress inducing layer is 10 nm-500 nm.

20 As an embodiment, a reaction chamber has a temperature ranging from 200°C to 500°C in the step of forming the stress inducing layer on the bottom p-i-n structure by utilizing the chemical vapor deposition process.

As an embodiment, a buffer layer is formed on the top p-i-n structure after the top p-i-n structure is formed and before the bottom p-i-n structure is
25 formed.

As an embodiment, the buffer layer is made of porous silicon containing P-type dopant or N-type dopant.

As an embodiment, the aperture diameter of the porous silicon is smaller than 1 μm .

5 As an embodiment, the buffer layer is formed by utilizing a photoelectric chemical etching process.

As an embodiment, the top p-i-n structure further includes a second p-i-n structure stacked on the first p-i-n structure, and the band gap of the I-type amorphous silicon layer of the first p-i-n structure is larger than the band gap of
10 the I-type layer of the second p-i-n structure.

As an embodiment, the second p-i-n structure includes a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer which are stacked in sequence or a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type
15 amorphous silicon layer which are stacked in sequence.

As an embodiment, the step of forming the first p-i-n structure and the second p-i-n structure which are stacked in sequence further comprises the steps of: introducing a first mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant into the reaction
20 chamber, so as to form the P-type amorphous silicon layer of the first p-i-n structure on the transparent conductive oxide layer; introducing a second mixed gas including hydrogen-containing gas and silicon-containing gas into the reaction chamber, so as to form the I-type amorphous silicon layer of the first p-i-n structure on the P-type amorphous silicon layer of the first p-i-n structure;
25 introducing a third mixed gas including hydrogen-containing gas,

silicon-containing gas and gas containing N-type dopant into the reaction chamber, so as to form the N-type amorphous silicon layer of the first p-i-n structure on the I-type amorphous silicon layer of the first p-i-n structure; introducing a first mixed gas including hydrogen-containing gas,
5 silicon-containing gas and gas containing P-type dopant into the reaction chamber, so as to form the P-type microcrystalline silicon layer or the P-type amorphous silicon layer of the second p-i-n structure on the N-type amorphous silicon layer of the first p-i-n structure; introducing a second mixed gas including hydrogen-containing gas and silicon-containing gas into the reaction chamber,
10 so as to form the I-type microcrystalline silicon layer or the I-type amorphous silicon layer of the second p-i-n structure on the P-type microcrystalline silicon layer or the P-type amorphous silicon layer of the second p-i-n structure, wherein the band gap of the I-type microcrystalline silicon layer or the I-type amorphous silicon layer of the second p-i-n structure is smaller than the band
15 gap of the I-type amorphous silicon layer of the first p-i-n structure; and introducing a third mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant into the reaction chamber, so as to form the N-type microcrystalline silicon layer or the N-type amorphous silicon layer of the second p-i-n structure on the I-type
20 microcrystalline silicon layer or the I-type amorphous silicon layer of the second p-i-n structure.

As an embodiment, the band gap of the I-type microcrystalline silicon layer of the second p-i-n structure is gradually reduced along the direction from the substrate to the back metal layer.

Compared with the prior art, the present disclosure has the advantages such as the following:

When the stress inducing layer is formed on the bottom p-i-n structure of the tandem solar cell, tensile strain is induced in the bottom p-i-n structure under the action of the stress inducing layer, so that the energy band gap of the I-type layer of the bottom p-i-n structure is reduced by 0.05 eV-0.15 eV, the absorbing wavelength range and the carrier mobility of the tandem solar cell are increased, the resistance is reduced, and thus the photoelectric conversion efficiency of the solar cell is improved.

Further, according to the tandem solar cell of the embodiments of the present disclosure, since the buffer layer is formed between the bottom p-i-n structure and the top p-i-n structure, the induced tensile stress in the bottom p-i-n structure during forming process of the solar cell does not affect the top p-i-n structure, which avoids change of the band gap of the top p-i-n structure.

In addition, according to the tandem solar cell of the embodiments of the present disclosure, the top p-i-n structure can be improved. For example, multiple p-i-n structures are formed in the top p-i-n structure and each p-i-n structure has an I-type layer with different band gaps, or an I-type layer with a variable band gap is formed in the top p-i-n structure, so that the absorbing wavelength range of the solar cell is increased.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 illustrates a schematic structure view of a common tandem solar cell;

Fig. 2 illustrates a schematic structure view of the tandem solar cell in the embodiment of the tandem solar cell of the present disclosure; and

Fig. 3 illustrates a production flow chart of the tandem solar cell in the embodiment of the production method of the tandem solar cell of the present disclosure.

DETAILED DESCRIPTION

A problem to be solved by the present disclosure is to provide a tandem solar cell with high photoelectric conversion efficiency and a production method thereof. As used herein, the singular forms “a,” “an” and “the” include plural referents unless the context clearly dictates otherwise.

It is noteworthy that, the P-type layer in the present disclosure refers to a photoelectric conversion material containing P-type dopant, e.g. amorphous silicon and microcrystalline silicon; the I-type layer refers to a photoelectric conversion material containing no P-type dopant or N-type dopant, e.g. amorphous silicon and microcrystalline silicon; and the N-type layer refers to a photoelectric conversion material containing N-type dopant, e.g. amorphous silicon and microcrystalline silicon.

In order to enable the tandem solar cell to have high photoelectric conversion efficiency, the present disclosure adopts the following measures: a stress inducing layer is formed on the bottom p-i-n structure of the tandem solar cell, and tensile strain is induced in the bottom p-i-n structure under the action of the stress inducing layer, so that the energy band gap of the I-type layer of the bottom p-i-n structure is reduced by 0.05 eV-0.15 eV, the absorbing

wavelength range is widened, the carrier mobility of the tandem solar cell is increased, the resistance is reduced, and thus the photoelectric conversion efficiency of the solar cell is improved.

In addition, on the basis of the above tandem solar cell, in order to prevent the stress induced in the bottom p-i-n structure during forming process of the solar cell from affecting the top p-i-n structure and avoid the change of the band gap of the top p-i-n structure, a buffer layer is formed between the bottom p-i-n structure and the top p-i-n structure.

On the basis of the above tandem solar cell, the top p-i-n structure can be improved. For example, multiple p-i-n structures are formed in the top p-i-n structure and each p-i-n structure has an I-type layer with different band gaps, or an I-type layer with a variable band gap is formed in the top p-i-n structure, so that the absorbing wavelength range of the solar cell is increased.

The technical solution of the present disclosure is described clearly and completely through specific embodiments by referring to accompanying figures. Apparently, the described embodiments are only a part of the embodiments of the present disclosure. According to the described and illustrated embodiments, all other embodiments can be easily devised by those of ordinary skills in the art without departing from the scope and spirit of the invention as defined in the appended claims.

Fig. 2 illustrates a schematic structure view of the tandem solar cell in the embodiment of the tandem solar cell of the present disclosure. As shown in Fig. 2, the tandem solar cell 10 includes a substrate 11, a transparent conductive oxide (TCO) layer 12 formed on the substrate 11, a top p-i-n structure 13 formed on the transparent conductive oxide layer 12, a bottom p-i-n

structure 14 formed on the top p-i-n structure 13, a stress inducing layer 15 formed on the bottom p-i-n structure 14, and a back metal layer 16 formed on the stress inducing layer 15.

The substrate 11 is made of transparent conductive materials such as glass, plastics, polymers and metal.

The transparent conductive oxide layer 12 contains suitable materials such as stannic oxide, zinc oxide, indium tin oxide, cadmium tannins and a combination thereof, and also contains other doping constituents. For example, when the transparent conductive oxide layer 12 is made of zinc oxide, constituents such as aluminum, gallium and boron can be doped in zinc oxide.

The top p-i-n structure 13 at least includes a first p-i-n structure 13a, and the first p-i-n structure 13a includes a P-type amorphous silicon (a-Si:H) layer 131a, an I-type amorphous silicon (i.e., intrinsic amorphous silicon) layer 132a and an N-type amorphous silicon layer 133a which are stacked in sequence, wherein the P-type amorphous silicon layer 131a is adjacent to the transparent conductive oxide layer 12.

The top p-i-n structure 13 further includes a second p-i-n structure 13b stacked on the first p-i-n structure 13a, and the band gap of the I-type amorphous silicon layer of the first p-i-n structure 13a is larger than the band gap of the I-type layer of the second p-i-n structure 13b. The second p-i-n structure 13b includes a P-type microcrystalline silicon layer 131b, an I-type microcrystalline silicon layer 132b and an N-type microcrystalline silicon layer 133b which are stacked in sequence or a P-type amorphous silicon layer 131b, an I-type amorphous silicon layer 132b and an N-type amorphous silicon layer 133b which are stacked in sequence. In one embodiment of the present

disclosure, the second p-i-n structure 13b includes a P-type microcrystalline silicon layer 131b, an I-type microcrystalline silicon layer 132b and an N-type microcrystalline silicon layer 133b which are stacked in sequence, and the band gap of the I-type microcrystalline silicon layer 132b of the second p-i-n structure 5 13b is gradually reduced along the direction from the substrate 11 to the back metal layer 16. Therefore, the band gap of the I-type microcrystalline silicon layer 132b near the substrate 11 is bigger than the band gap of the I-type microcrystalline silicon layer 132b near the back metal layer 16. The top p-i-n structure 13 with the above structure enables the absorbing wavelength range 10 of the tandem solar cell to be increased and widened. The absorbing wavelength range of a tandem solar cell with the above structure is larger than a tandem solar cell without the above structure.

The bottom p-i-n structure 14 includes a P-type microcrystalline silicon ($\mu\text{c-Si:H}$) layer 141, an I-type microcrystalline silicon layer 142 and an N-type 15 microcrystalline silicon layer 143 which are stacked in sequence, wherein the P-type microcrystalline silicon layer 141 is adjacent to the top p-i-n structure 13.

When the stress inducing layer 15 is formed on the bottom p-i-n structure 14, the bottom p-i-n structure 14 is induced to generate tensile strain which is not exceeding 1% under the action of the stress inducing layer 15, so that the 20 energy band gap of the I-type layer of the bottom p-i-n structure 14 is reduced by 0.05 eV-0.15 eV, the absorbing wavelength range is widened, the carrier mobility is increased, the resistance is reduced, and the photoelectric conversion efficiency is improved.

Multiple materials are available for the stress inducing layer 15 as long 25 as the tensile stress can be introduced in the bottom p-i-n structure 14 during

forming process of the stress inducing layer 15 on the bottom p-i-n structure 14. In this embodiment, the stress inducing layer 15 is made of tungsten, silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride.

For the stress inducing layer 15 made of tungsten, tungsten atom exists
5 at the crystal boundary and the crystal cell also comprises tungsten, which introduces stress in the stress inducing layer 15 made of tungsten, and when tungsten is deposited on the bottom p-i-n structure, the stress introduced by the stress inducing layer 15 is released on the bottom p-i-n structure 14 and introduces stress in the bottom p-i-n structure 14. Since the stress inducing
10 layer 15 which is made of silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride has an asymmetrical or complicated lattice structure, adjacent atoms extrude each other and introduces stress in the stress inducing layer 15, and when silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride is deposited on the bottom p-i-n structure 14, the stress introduced by the stress
15 inducing layer 15 is released on the bottom p-i-n structure 14 and introduces stress in the bottom p-i-n structure 14. The thickness of the stress inducing layer 15 is closely related to the stress introduced by the stress inducing layer 15 to the bottom p-i-n structure 14. In order to prevent cracking of the bottom p-i-n structure 14 resulted from overlarge tensile stress introduced by the stress
20 inducing layer 15 to the bottom p-i-n structure 14, the thickness of the stress inducing layer 15 is set to be 10 nm-500 nm.

The materials of the back metal layer 16 include but not limited to Al, Ar, Ag, Ti, Cr, Au, Cu, Pt and an alloy or a combination thereof.

The top p-i-n structure 13 absorbs sunlight to generate electron-hole
25 pairs. An electric field generated between the P-type layer of the top p-i-n

structure 13 and the N-type layer of the top p-i-n structure 13 enables the electrons move towards the N-type layer of the top p-i-n structure 13 and the holes flow towards the P-type layer of the top p-i-n structure 13, so as to form a current and light energy is converted into electric energy. Since the band gap of amorphous silicon is larger than the band gap of microcrystalline silicon, the microcrystalline silicon absorbs light with wide wave band, while the amorphous silicon absorbs light with narrow wave band. Sunlight first irradiates the top p-i-n structure 13 and is absorbed by the I-type layer thereof, and sunlight which is not absorbed by the top p-i-n structure 13 penetrates and irradiates the bottom p-i-n structure 14 and absorbed by the bottom p-i-n structure 14 to generate electron-hole pairs. An electric field generated between the P-type microcrystalline silicon layer 141 of the bottom p-i-n structure 14 and the N-type microcrystalline silicon layer 143 of the bottom p-i-n structure 14 enables the electrons move towards the N-type microcrystalline silicon layer 143 and the holes flow towards the P-type microcrystalline silicon layer 141, so as to form a current. Thus, light energy is converted into electric energy.

In order to prevent the stress induced by the stress inducing layer 15 during forming process of the tandem solar cell 10 from affecting the top p-i-n structure 13 and change the band gap of the top p-i-n structure 13. To form a buffer layer 17 between the bottom p-i-n structure 14 and the top p-i-n structure 13, so that the tensile stress induced in the bottom p-i-n structure 14 which transferring into the buffer layer 17 is absorbed or weakened by the buffer layer 17. Through the said structure, there has no stress or little stress (not more than 1%) transfer into the top p-i-n structure 13 below the buffer layer 17. Variety of

materials are suitable for the buffer layer 17, in this embodiment, the buffer layer 17 is porous silicon. Multiple holes are formed in the porous silicon, and the aperture diameter of the porous silicon is preferably smaller than 1 μm , thereby having great elastic deformation capability, and effectively reducing or eliminating stress transferred to the porous silicon. P-type doping or N-type doping is performed on the porous silicon, so that the top p-i-n structure 13 is electrically conducted to the bottom p-i-n structure 14.

Fig. 3 illustrates a production flow chart of the tandem solar cell in the embodiment of the production method of the tandem solar cell of the present disclosure. The embodiment of the production method of the tandem solar cell in is described in details with reference to both Figs. 2 and 3.

First, step S11 is performed, providing a substrate 11 to the reaction chamber (not shown).

Next, step S12 is performed, forming a transparent conductive oxide layer 12 on the substrate 11, wherein multiple forming method are available, such as a sputtering method, a chemical vapor deposition (CVD) method and an arc plasma method.

Subsequently, step S13 is performed, forming a top p-i-n structure 13 on the transparent conductive oxide layer 12. The top p-i-n structure 13 at least includes a first p-i-n structure 13a, and the first p-i-n structure 13a includes a P-type amorphous silicon (a-Si:H) layer 131a, an I-type amorphous silicon (i.e., intrinsic amorphous silicon) layer 132a and an N-type amorphous silicon layer 133a which are stacked in sequence, wherein the P-type amorphous silicon layer 131a is adjacent to the transparent conductive oxide layer 12.

The top p-i-n structure 13 may further include a second p-i-n structure 13b stacked on the first p-i-n structure 13a, and the band gap of the I-type amorphous silicon layer of the first p-i-n structure 13a is larger than the band gap of the I-type layer of the second p-i-n structure 13b. The I-type layer of the second p-i-n structure 13b can be I-type amorphous silicon layer or I-type microcrystalline silicon layer; therefore the second p-i-n structure 13b includes a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer which are stacked in sequence or a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type amorphous silicon layer which are stacked in sequence. In an embodiment of the present disclosure, the second p-i-n structure 13b includes a P-type microcrystalline silicon layer 131b, an I-type microcrystalline silicon layer 132b and an N-type microcrystalline silicon layer 133b which are stacked in sequence, and the band gap of the I-type microcrystalline silicon layer of the second p-i-n structure 13b is gradually reduced along the direction from the substrate 11 to the back metal layer 16.

In this embodiment, the P-type amorphous silicon layer 131a of the first p-i-n structure 13a is formed by plasma enhanced chemical vapor deposition (PECVD) method, and the method includes: introducing a first mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant into the reaction chamber, so as to form the P-type amorphous silicon layer 131a on the transparent conductive oxide layer. The hydrogen-containing gas includes but not limited to hydrogen. The silicon-containing gas includes but not limited to silane (SiH_4), disilane (Si_2H_6), silicon tetrafluoride (SiF_4), silicon tetrachloride (SiCl_4), dichloro-silane (SiH_2Cl_2)

and a combination thereof. The P-type dopant may include III-family elements such as boron or aluminum, and preferably is boron. The boron-containing gas may include trimethyl boron (TMB or $B(CH_3)_3$), diborane (B_2H_6), BF_3 and $B(C_2H_5)_3$.

5 The forming method of the I-type amorphous silicon layer 132a of the first p-i-n structure 13a is like that of the P-type amorphous silicon layer 131a, and the difference is that the gas containing P-type dopant does not need to be introduced into the reaction chamber during the forming process. Specifically, the forming method includes the following steps: introducing a second mixed
10 gas including hydrogen-containing gas and silicon-containing gas into the reaction chamber, so as to form the I-type amorphous silicon layer 132a on the P-type amorphous silicon layer 131a.

 The N-type amorphous silicon layer 133a of the first p-i-n structure 13a can also be formed by adopting a plasma enhanced chemical vapor deposition
15 (PECVD) method, and the method includes: introducing a third mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant into the reaction chamber, so as to form the N-type amorphous silicon layer 133a on the I-type amorphous silicon layer 132a. The hydrogen-containing gas includes but not limited to hydrogen. The
20 silicon-containing gas includes but not limited to silane (SiH_4), disilane (Si_2H_6), silicon tetrafluoride (SiF_4), silicon tetrachloride ($SiCl_4$), dichloro-silane (SiH_2Cl_2) and a combination thereof. The gas containing N-type dopant includes V-family elements such as phosphorus, arsenic or antimony, and preferably is phosphorus. The phosphorus-containing gas may include hydrogen
25 phosphide and the like. Thus, the first p-i-n structure 13a is formed.

Similarly, the second p-i-n structure 13b can also be formed by using a plasma enhanced chemical vapor deposition (PECVD) method, and the method includes: introducing a first mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant into the reaction chamber, so as to form the P-type amorphous silicon layer or the P-type microcrystalline silicon layer 131b of the second p-i-n structure 13b on the N-type amorphous silicon layer 133a of the first p-i-n structure 13a; then introducing a second mixed gas including hydrogen-containing gas, silicon-containing gas and dopant into the reaction chamber, so as to form the I-type amorphous silicon layer or the I-type microcrystalline silicon layer 132b on the P-type amorphous silicon layer or the P-type microcrystalline silicon layer 131b of the second p-i-n structure 13b, wherein the energy band gap of the I-type layer (including the I-type amorphous silicon layer or the I-type microcrystalline silicon layer) 132b of the second p-i-n structure 13b is smaller than that of the I-type amorphous silicon layer 132a of the first p-i-n structure 13a. When the I-type layer of the second p-i-n structure 13b is the I-type amorphous silicon layer, other dopants can be added into the mixed gas forming the I-type amorphous silicon layer, such as germanium, so as to change the energy band gap of the I-type amorphous silicon layer.

Introducing a third mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant into the reaction chamber, so as to form the N-type amorphous silicon layer or the N-type microcrystalline silicon layer 133b on the I-type amorphous silicon layer or the I-type microcrystalline silicon layer 132b of second p-i-n structure 13b.

The introduction of gas into the reaction chamber can be continued so as to form other p-i-n structures on the second p-i-n structure 13b, and it is not illustrated any more.

Next, step S14 is performed, forming a buffer layer 17 on the top p-i-n structure 13.

A variety of materials are selected for the buffer layer 17. In this embodiment, the buffer layer 17 is made of porous silicon, and P-type doping or N-type doping is performed on the porous silicon, so that the top p-i-n structure 13 is electrically conducted to the bottom p-i-n structure 14. The buffer layer 17 is formed by utilizing a relatively mature production process, i.e., the photoelectric chemical etching process, and the technological parameters of the production process is as follows: the temperature is room temperature, the current density is 5 mA/cm²-800 mA/cm², the irradiation optical power of halogen light is 10 mW/cm²-100 mW/cm², and the solution is the mixed solution of hydrofluoric acid (HF), water (H₂O) and alcohol (C₂H₅OH).

Next step S15 is performed, forming a bottom p-i-n structure 14 on the buffer layer 17, wherein the bottom p-i-n structure 14 includes sequential stacked a P-type microcrystalline silicon layer 141, an I-type microcrystalline silicon layer 142 and an N-type microcrystalline silicon layer, wherein the P-type microcrystalline silicon layer 141 is close and adjacent to the top p-i-n structure 13. The forming methods of the microcrystalline silicon layer can be plasma enhanced chemical vapor deposition (PECVD), hot wire chemical vapor deposition (HWCVD) or electron cyclotron resonance chemical vapor deposition, in this embodiment, plasma enhanced chemical vapor deposition (PECVD) is taken as an example.

The microcrystalline silicon layer forming method comprises: introducing a first mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant into the reaction chamber, so as to form the P-type microcrystalline silicon layer 141 on the buffer layer 17. During the forming process of the P-type microcrystalline silicon layer 141, the proportion of hydrogen-containing gas in the first mixed gas is controlled and other technical parameters are also controlled to enable the microcrystalline silicon layer to have a proper crystallization rate. For example, the crystallization rate is kept between 20% and 80%.

The forming method of the I-type microcrystalline silicon layer 142 is basically the same as that of the P-type microcrystalline silicon layer 141, and the difference is that the gas containing P-type dopant does not need to be introduced into the reaction chamber during the forming process. Specifically, the forming method includes the forming steps: introducing a second mixed gas including hydrogen-containing gas and silicon-containing gas into the reaction chamber, so as to form the I-type microcrystalline silicon layer 142 on the P-type microcrystalline silicon layer 141.

The forming method of the N-type microcrystalline silicon layer 143 is basically the same as that of the P-type microcrystalline silicon layer 141, and the difference is that the gas containing N-type dopant is instead introduced into the reaction chamber during the forming process. Specifically, the forming method includes the following steps: introducing a third mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant into the reaction chamber, so as to form the N-type microcrystalline silicon layer 143 on the I-type microcrystalline silicon layer 142. During the

forming process of the N-type microcrystalline silicon layer 143, the proportion of hydrogen-containing gas in the third mixed gas is controlled and other technical parameters are also controlled to enable the microcrystalline silicon layer to have a proper crystallization rate. For example, the crystallization rate is kept between 20% and 80%.

Next step S16 is performed, forming a stress inducing layer 15 on the bottom p-i-n structure 14. Multiple materials are available for the stress inducing layer 15. In this embodiment, the stress inducing layer 15 is made of tungsten, silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride.

During the forming process of the stress inducing layer 15, tensile stress is introduced inside the bottom p-i-n structure 14 so as to improve the photoelectric conversion efficiency of the tandem solar cell 10. Multiple forming methods are available to the stress inducing layer 15, and in this embodiment, the stress inducing layer 15 is formed by utilizing the chemical vapor deposition process. When the stress inducing layer 15 is formed by utilizing the chemical vapor deposition process, it is found that the stress induced by the stress inducing layer 15 to the bottom p-i-n structure 14 can be adjusted by controlling the technological parameters of the chemical vapor deposition process. In this embodiment, when the temperature in the reaction chamber is kept between 200°C and 500°C, proper tensile strain is induced in the bottom p-i-n structure 14 and the bottom p-i-n structure 14 obtains high photoelectric conversion efficiency. Furthermore, when the stress inducing layer 15 is formed, the bottom p-i-n structure 14 is monitored to ensure that the tensile deformation of the bottom p-i-n structure 14 does not exceed 1%, so as to avoid the situation that high photoelectric conversion efficiency cannot be

obtained due to the internal structure damage resulted from overlarge deformation made in the bottom p-i-n structure 14. The thickness of the stress inducing layer 15 is highly related to the stress introduced by the stress inducing layer 15 to the bottom p-i-n structure 14. In order to prevent cracking of the bottom p-i-n structure 14 resulted from overlarge tensile stress introduced by the stress inducing layer 15 to the bottom p-i-n structure 14, the thickness of the stress inducing layer 15 is set to be 10 nm-500 nm.

Subsequently, step S17 is performed, forming a back metal layer 16 on the stress inducing layer 15, wherein the forming method of the back metal layer 16 is the same as that of the transparent conductive oxide layer 12.

In the above process of producing the tandem solar cell, although the P-type layers, the I-type layers and the N-type layers of the top p-i-n structure 13 (including the first p-i-n structure 13a and the second p-i-n structure 13b) and the bottom p-i-n structure 14 are each formed by utilizing a first mixed gas (including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant), a second mixed gas (including hydrogen-containing gas and silicon-containing gas) and a third mixed gas (including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant), during forming of the P-type layers, the I-type layers and the N-type layers of different p-i-n structures, the proportion of various gases in the first mixed gas, the second mixed gas and the third mixed gas probably needs to be adjusted correspondingly, or different kinds of hydrogen-containing gas, silicon-containing gas, gas containing P-type dopant and gas containing N-type dopant are used. In addition, during forming of the P-type layers, the I-type layers and the N-type layers of different p-i-n structures, specific technical

parameters such as reaction pressure and temperature also need to be adjusted correspondingly.

In conclusion, compared with the prior art, the present disclosure has the following advantages:

5 when the stress inducing layer is formed on the bottom p-i-n structure of the tandem solar cell, tensile strain is made in the bottom p-i-n structure under the action of the stress inducing layer, so that the energy band gap of the I-type layer of the bottom p-i-n structure is reduced by 0.05 eV-0.15 eV, the absorbing wavelength range is widened, the carrier mobility of the tandem solar cell is
10 increased, the resistance is reduced, and thus the photoelectric conversion efficiency of the solar cell is improved.

On the basis of the above tandem solar cell, since the buffer layer is formed between the bottom p-i-n structure and the top p-i-n structure, stress introduced in the bottom p-i-n structure during the forming process of the solar
15 cell does not affect the top p-i-n structure, which avoids change of the band gap of the top p-i-n structure. According to the above tandem solar cell, the top p-i-n structure can be improved, for instance, multiple p-i-n structures are formed in the top p-i-n structure and each p-i-n structure has an I-type layer with energy band gap, or an I-type layer with a variable band gap is formed in the top p-i-n
20 structure, so that the absorbing wavelength range of the solar cell is increased and widened.

In the forgoing, with reference to the above description of the embodiments, those of professional skills in the art can better understand, reproduce and use the present disclosure. It will be apparent to those of
25 professional skills in the art that various modifications and variations can be

made to the embodiments without departing from the scope or spirit of the present disclosure according to the principles described in the embodiments.

Thus, it should be understood that these embodiments are not intended to limit the present disclosure, and the scope of the present disclosure shall be defined

5 by the appended claims.

WHAT IS CLAIMED IS:

1. A tandem solar cell, comprising:

a substrate;

5 a transparent conductive oxide layer formed on the substrate;

a top p-i-n structure formed on the transparent conductive oxide layer and comprising a first p-i-n structure, wherein the first p-i-n structure comprises a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type amorphous silicon layer which are stacked in sequence, wherein the
10 P-type amorphous silicon layer is adjacent to the transparent conductive oxide layer;

a bottom p-i-n structure formed on the top p-i-n structure, wherein the bottom p-i-n structure comprises a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer
15 which are stacked in sequence, wherein the P-type microcrystalline silicon layer is adjacent to the top p-i-n structure;

a stress inducing layer formed on the bottom p-i-n structure, the stress inducing layer induces tensile stress in the bottom p-i-n structure; and

a back metal layer formed on the stress inducing layer.

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2. The tandem solar cell of claim 1, wherein the stress inducing layer is made of tungsten, silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride.

3. The tandem solar cell of claim 2, wherein the stress inducing layer has a thickness of 10 nm to 500 nm.

4. The tandem solar cell of claim 1, further comprising a buffer layer
5 formed between the top p-i-n structure and the bottom p-i-n structure.

5. The tandem solar cell of claim 4, wherein the buffer layer is made of porous silicon containing P-type dopant or N-type dopant.

10 6. The tandem solar cell of claim 5, wherein the aperture diameter of the porous silicon is smaller than 1 μm .

7. The tandem solar cell of claim 1 or 4, wherein the top p-i-n structure further comprises a second p-i-n structure with an I-type layer disposed on the
15 first p-i-n structure, wherein the band gap of the I-type amorphous silicon layer of the first p-i-n structure is larger than the band gap of the I-type layer of the second p-i-n structure.

8. The tandem solar cell of claim 7, wherein the second p-i-n structure
20 comprises a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer which are stacked in sequence or a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type amorphous silicon layer which are stacked in sequence.

9. The tandem solar cell of claim 8, wherein the energy band gap of the I-type microcrystalline silicon layer of the second p-i-n structure is gradually reduced along the direction from the substrate to the back metal layer.

- 5 10. A method of fabricating a tandem solar cell, comprising the steps of:
providing a substrate;
forming a transparent conductive oxide layer on the substrate;
forming a top p-i-n structure on the transparent conductive oxide layer,
which comprises a first p-i-n structure, wherein the first p-i-n structure
10 comprises a P-type amorphous silicon layer, an I-type amorphous silicon layer
and an N-type amorphous silicon layer which are stacked in sequence, wherein
the P-type amorphous silicon layer is adjacent to the transparent conductive
oxide layer;
forming a bottom p-i-n structure on the top p-i-n structure, the bottom
15 p-i-n structure comprising a P-type microcrystalline silicon layer, an I-type
microcrystalline silicon layer and an N-type microcrystalline silicon layer which
are stacked in sequence, wherein the P-type microcrystalline silicon layer is
adjacent to the top p-i-n structure;
forming a stress inducing layer on the bottom p-i-n structure, wherein
20 stress inducing layer induced tensile stress in the bottom p-i-n structure during
the forming process of the stress inducing layer; and
forming a back metal layer on the stress inducing layer.

11. The method of claim 10, wherein the stress inducing layer is formed
25 by utilizing a chemical vapor deposition process.

12. The method of claim 10, wherein the stress inducing layer is made of tungsten, silicon nitride, silicon oxide, silicon oxynitride or tungsten nitride.

5 13. The method of claim 10, wherein the stress inducing layer has a thickness of 10 nm-500 nm.

14. The method of claim 11, wherein, in the step of forming the stress inducing layer on the bottom p-i-n structure by utilizing the chemical vapor
10 deposition process, a temperature of reaction chamber is from 200°C to 500°C.

15. The method of claim 10, further comprising a step of forming a buffer layer on the top p-i-n structure after the step of forming the top p-i-n structure and before the step of forming the bottom p-i-n structure.

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16. The method of claim 15, wherein the buffer layer is made of porous silicon containing P-type dopant or N-type dopant.

17. The method of claim 16, wherein the aperture diameter of the porous
20 silicon is smaller than 1 μm .

18. The method of claim 15, wherein the buffer layer is formed by utilizing a photoelectric chemical etching process.

19. The method of claim 10 or 15, wherein the top p-i-n structure further comprises a second p-i-n structure with a I-type layer stacked on the first p-i-n structure, and the band gap of the I-type amorphous silicon layer of the first p-i-n structure is larger than the band gap of the I-type layer of the second p-i-n structure.

20. The method of claim 19, wherein the second p-i-n structure comprises a P-type microcrystalline silicon layer, an I-type microcrystalline silicon layer and an N-type microcrystalline silicon layer which are stacked in sequence or a P-type amorphous silicon layer, an I-type amorphous silicon layer and an N-type amorphous silicon layer which are stacked in sequence.

21. The method of claim 20, wherein the step of forming the first p-i-n structure and the second p-i-n structure which are stacked in sequence further comprises the steps of:

introducing a first mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant into the reaction chamber, so as to form the P-type amorphous silicon layer of the first p-i-n structure on the transparent conductive oxide layer;

introducing a second mixed gas including hydrogen-containing gas and silicon-containing gas into the reaction chamber, so as to form the I-type amorphous silicon layer of the first p-i-n structure on the P-type amorphous silicon layer of the first p-i-n structure;

introducing a third mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant into the reaction

chamber, so as to form the N-type amorphous silicon layer of the first p-i-n structure on the I-type amorphous silicon layer of the first p-i-n structure;

introducing a first mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing P-type dopant into the reaction chamber, so as to form the P-type microcrystalline silicon layer or the P-type amorphous silicon layer of the second p-i-n structure on the N-type amorphous silicon layer of the first p-i-n structure;

introducing a second mixed gas including hydrogen-containing gas and silicon-containing gas into the reaction chamber, so as to form the I-type microcrystalline silicon layer or the I-type amorphous silicon layer of the second p-i-n structure on the P-type microcrystalline silicon layer or the P-type amorphous silicon layer of the second p-i-n structure, wherein the band gap of the I-type microcrystalline silicon layer or the I-type amorphous silicon layer of the second p-i-n structure is smaller than the band gap of the I-type amorphous silicon layer of the first p-i-n structure; and

introducing a third mixed gas including hydrogen-containing gas, silicon-containing gas and gas containing N-type dopant into the reaction chamber, so as to form the N-type microcrystalline silicon layer or the N-type amorphous silicon layer of the second p-i-n structure on the I-type microcrystalline silicon layer or the I-type amorphous silicon layer of the second p-i-n structure.

22. The method of claim 20, wherein the band gap of the I-type microcrystalline silicon layer of the second p-i-n structure is gradually reduced along the direction from the substrate to the back metal layer.